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## A quantum mixer at 350 GHz based on superconductor-insulator-superconductor (SIS) junctions.

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## 6 Summary and outlook

The central issue of this thesis is the application of the superior qualities of superconductor-insulator-superconductor (SIS) mixers at submillimeter wavelengths. After the discovery of photon assisted quasi particle tunnelling in SIS junctions, very low noise heterodyne mixers, employing these junctions as mixing element have been developed at millimeter frequencies. At these frequencies the voltage span associated with the photon energy,  $hf/e$ , is large enough to cause clearly defined photon assisted tunnelling steps at a good quality SIS DC IV-curve. If that is the case the junction functions as a quantum mixer, for which a quantum limited noise contribution and possible conversion gain are predicted. At 37 GHz and around 100 GHz very low noise temperatures have indeed been realized with SIS mixers, much lower than with Schottky diodes that behave as classical resistive mixers.

A difficulty in the use of SIS junctions compared to Schottky diodes is the matching to the incident signal. Due to the geometrical capacitance of the SIS junction parallel to the tunnel barrier, the typical response time of a junction is generally larger than the inverse of the frequency. The response time is dependent on the barrier thickness of the junction and decreasing the barrier thickness has resulted in junctions that have a response time low enough to function as mixers at millimeter wavelengths. For long response times, the junction capacitance is compensated at the signal frequency by a matching network. This approach results in a mixer with a smaller instantaneous bandwidth. The reported receiver noise temperatures are generally lower for the latter approach however, probably because harmonic responses in the mixer element are more effectively shorted.

At submillimeter wavelengths it is unlikely that the response time can be made small enough by reducing the barrier thickness, without seriously affecting the quality of the junction. The design, as described in Chapter 2, is therefore based on the assumption that the geometrical capacitance has to be compensated at the signal frequency. The design is basically a scaling of comparable approaches at millimeter wavelengths. The difficulty involved is the technical realisation of the scaled dimensions. The response time (RC) of the junction determines the maximum instantaneous bandwidth (BW) of the mixer by  $BW=1/(\omega RC)$ , where  $\omega$  is  $2\pi$  times the LO frequency. To achieve the required instantaneous bandwidth of at least 10 %, very small barrier thicknesses have to be used. Except for the technical difficulties involved, it also results in a decrease of the normal state resistance,  $R$ , of the junction to a value that is very difficult to match. To make the matching possible the junction areas is decreased to obtain a reasonable value ( $20 \Omega < R < 80 \Omega$ ) for  $R$ . This scaling of junction dimensions has required a substantial technological effort, in order to realise the SIS junctions in Nb-Al<sub>2</sub>O<sub>3</sub>-Nb technology integrated with components required at these frequencies. This is described in Chapter 3.

Even with the mentioned values of the normal state resistance the requirements on the matching are severe, because of the low response times. As a conservative approach, based on results reported at millimeter wavelengths, a waveguide mount was chosen to realize the matching network. The incident signal is coupled from free space into the waveguide with a diagonal horn antenna. The advantage of a waveguide mount is that the tuning can be adjusted for optimum performance during operation of the mixer. For an arbitrary structure two waveguide tuners, a backshort and an E-plane tuner, are necessary to match the waveguide impedance to the junction, as is shown in Chapter 2 from scaled

model measurements. A numerical model is developed for the waveguide structure to calculate the impedances from the physical dimensions of the structure, which show good correspondence with the scaled model measurements.

Two ways to reduce the number of adjustable tuning elements are explored in Chapter 2. It is shown that a perfect match between the waveguide and a comparable junction can also be reached with a single backshort if the first section of the low pass filter that connects the junction with DC and IF connections is adapted. In the numerical model, based on the scaled model two ad hoc adjustments had to be made to adapt the model for this modification. More work is required in the future to express the effect of the modification in the physical dimensions of the components. As a second approach to reduce the number of adjustable tuning elements, fixed integrated tuning by a superconducting transmission line directly at the junction, is applied. While this type of tuning has the benefit of achieving a nearly perfect match over a much larger bandwidth, it makes the final matching more dependent on fabrication parameters, especially on the exact junction area and on the properties of the superconducting layers. Only one of the simplest forms of this type of integrated tuning, an open circuited stub, has been investigated in this work. With this simple structure improvement of a factor of 3 to 4 in bandwidth compared to the other structures is measured, using a comparable junction. In addition to the different ways of tuning also series arrays of junctions (2 and 4) are applied to optimize the matching.

Design work in a scaled model cannot give an estimate for the losses in the real waveguides. The increasing loss in waveguides at frequencies where the penetration depth approaches the manufacturing tolerances is a major concern in using waveguides at high frequencies. Measurements at room temperature at 350 GHz, using a thin film bismuth bolometer instead of a SIS junction, are reported in Chapter 3. It appears that the propagation loss is lower than 44 dB/m, which shows that there is only a limited influence of the surface roughness. For the adjustable tuning elements values of 200 have been realized for the VSWR, which is more than sufficient for the matching design. It is shown that sliding shorts with high/low impedance sections to improve the reflection, show a better performance than ordinary contacting sliding shorts.

Also at 4.2 K losses do not have a major influence on the embedding impedance of the tested SIS mixers at 350 GHz. The influence of the losses is tested systematically in a waveguide mixerblock with a single backshort, employing junctions without integrated tuning. In this configuration, which is also very well to model, losses have the largest influence on the performance. It is concluded from the measurements, that there is no additional loss observed beyond what was expected from the quality measurement of the backshorts at room temperature. As a consequence a perfect match between the waveguide and the SIS junction is reached with a mixerblock with one backshort according to the design, as has been verified by determining the embedding impedance in the real mixer. In comparing the receiver noise temperatures measured in the mixers at 350 GHz and in the scaled design at 490 GHz, it appears that up to 500 GHz waveguide losses do not dominate the receiver performance.

Embedding impedances in the real mixer are determined from a comparison of the pumped and unpumped IV-curves. In Chapter 4, a comparison between these impedances and impedances predicted from the model show very good agreement. For structures without integrated tuning there is a minor, systematic, difference observed for structures where the length of the first filter section is very critical. This emphasizes the fact that although the correspondence between calculated and measured embedding impedances is

actually very good, the embedding impedance is especially true for the properties of the superconducting junction.

The general conclusion is that the match is not completely perfect at the frequency of perfect match. The best match at the point of optimum performance is always a little capacitor. This choice for the low IF input impedance with a positive slope.

The values have an important influence separately. If they are indeed measured, (1sb) and upper sideband usually results in a optimum performance obtained from pump ratios a single sideband.

Although the performance, the coupling appears that the frequency is rather well by the detection mode. Because at room temperature the ins coupling at the LO side impedance at the proximity of the irrelevant whether two or four junctions to design mixers with three port approximation.

A difference in The mixer noise temperature and is usually only varies considerably temperature because larger instantaneous influence of the embedding impedances integrated tuning co temperature is in much higher mixer gain, a

The extensive

actually very good and the model is very useful in predicting those, accurate values for the embedding impedance are best obtained from the DC IV-curves of the junction. This is especially true for tuning configurations in which integrated tuning is applied. The properties of the superconducting transmission line are difficult to predict accurately.

The general assumption underlying the design work, that the mixer must be well matched at the local oscillator (LO) frequency to ensure optimum SIS mixer performance, is not completely accurate. In a two tuner mixer, where a perfect match at the LO frequency can be easily achieved, optimum mixer performance is never measured at the point of perfect match for the LO. In the single tuner mixer the junction that shows the best match at the LO frequency, even shows the worst noise temperature. It appears that at the point of optimum mixer performance the embedding impedance at the LO frequency is always a little capacitive. This is also the case when an integrated tuned junction is used. This choice for the optimum LO embedding impedance maybe partly due to the relatively low IF input impedances. A low source impedance at the IF, requires a pumped IV-curve with a positive slope, which is obtained for a capacitive embedding impedance.

The values of the embedding impedances at both side band frequencies, which have an important influence on the mixer performance, can in most cases not be adjusted separately. If they can, as is the case in the two tuner mixer, lower noise temperatures are indeed measured. All measured mixer parameters are an addition of the lower side band (lsb) and upper side band (usb) performance. Consequently an optimization of the mixer usually results in a compromise between the two side band conversions. At most points of optimum performance the side band ratio, calculated from the embedding impedances obtained from pumped IV-curves, is close to unity. To optimize for different side band ratios a single side band filter should be implemented at the input of the mixer.

Although the side band impedances have an important influence on the mixer performance, the coupling at the LO frequency can still provide useful information. It appears that the frequency dependence of the mixer gain at fixed tuning, is predicted rather well by the frequency dependence of the coupling at the LO, measured in a direct detection mode. Because of the important influence of the mixer gain on the receiver noise temperature the instantaneous bandwidth of the mixer is also well predicted by the coupling at the LO frequency. The dependence of the mixer performance on the embedding impedance at LO, usb, and lsb frequency is well predicted by a three port approximation of the quantum theory of mixing, as is shown in Chapter 5. Thereby it is irrelevant whether the mixing element consists of a single junction, or of a series array of two or four junctions. If the initial matching problems are overcome, it appears advisable to design mixers with optimum performance using the quantum theory of mixing. The three port approximation of the theory appears to be sufficient at these high frequencies.

A difference has to be made between mixer performance and receiver performance. The mixer noise temperature  $T_m$  is a rather weak function of the embedding impedance, and is usually only a small part of the receiver noise. The mixer gain (or loss) however varies considerably with the embedding. It is an important parameter in the receiver noise temperature because it determines the contribution of the IF, by  $T_H/G_m$ . Structures with a larger instantaneous bandwidth show a higher mixer gain, which is a direct effect of the influence of the embedding impedance of the side band frequencies. For structures with integrated tuning compared to structures without integrated tuning, a lower receiver noise temperature is in most cases due to a reduction of the IF-contribution, because of the higher mixer gain, as is shown in Chapter 4.

The extensive study of six different samples at various embedding impedances in

Chapter 5 shows further that although the measured dependence of the mixer performance on the embedding impedance, and also on bias voltage is well predicted by the quantum theory of mixing, the absolute values of the mixer gain and mixer noise are not. There is a systematic difference in the absolute values of the predicted and the measured mixer gain and noise. In all cases the measured mixer noise temperature is about 50 K higher than predicted and the measured mixer gain approximately a factor of two lower. These differences are significant, because the accuracy of the experiments, due to an in situ calibration of the IF and an accurate determination of the transmission of the input optics, is 7% in the gain and  $\pm 15$  K for the noise temperatures. Attempts to explain the difference between measurement and calculation from saturation, a five port approximation instead of a three port approximation or inaccuracies in the calculation have failed. A possible explanation for the difference in mixer gain should be sought in the optics on the 4.2 K plate of the dewar. A satisfactory explanation for the excess mixer noise has not been found. One possible explanation is indicated by the observed correlation between the measured excess noise and the subgap current of the unpumped SIS junction. This suggests that the extra noise contributions are due to imperfections in the barrier.

Another possible explanation is suggested by the experiments with integrated tuned junctions. 50 K excess noise is approximately three times the quantum noise at 350 GHz, which means that quantum limited mixer noise performance has not been reached yet. The lowest measured receiver noise temperature, however, is 75 K at 357 GHz, with a junction with integrated tuning. Due to the high mixer gain the receiver noise temperature measured with this junction is lower over the whole frequency band than of a comparable junction without integrated tuning. The mixer noise temperature however is comparable for both junctions, except for one rather sharp dip near the resonance frequency, which results also in the low receiver noise. This dip appears to be very sensitive to the embedding impedances at both side band frequencies. A quick analysis of this effect shows that the mixer noise temperature at this point is approximately 50 K, implying that the difference between measurement and theory must be smaller than in the experiments mentioned above. Future work to determine the embedding impedance dependence of this effect maybe very interesting, both for the comparison between theory and practice, and to design mixers that reach the quantum noise limit. Future work involving the scaling of the mixer to an even higher frequency will reach the gap frequency of the junction electrode material. Predictions of mixer performance in that regime are not made yet.

## Samenvatting

Straling op  
tussen 300 GHz en  
wolken, en aan gas-  
bepaalde atomen of  
emissie of absorptie  
de snelheid uit de D  
ontvanger verkort d  
transmissie van de a  
gen vanaf het aardop  
in een droge atmo-  
telescopen gebruikt o  
vliegtuigen en toeko  
gedaan worden. De q  
(SIS) tunnel juncties

Aan de ene  
millimeter golf lengte  
kant ligt het ver infra  
Van beide naburige g  
mixer, een detectie m  
zwakke hoog frequen  
oscillator (LO), dat  
toegankelijke, lagere,  
signaal blijft hierbij  
gekaracteriseerd word  
beide signalen hoogfre  
signaal met als frequen  
hoog frequente signa  
spectrometers goed te  
verschil frequentie de b

SIS juncties w  
conversie efficiëntie C  
gebruikte Schottky di  
vermindert de, vaak aa  
totale ontvanger ruis. S  
vermogen in de IF ban  
bandbreedte ( $G_m \leq 1$ ). SI  
van een conversie effie  
wordt fundamenteel al  
minimale ruisbijdrage v  
waarneming bedraagt. U

Bij de aanvang  
toegepast in heterodyn  
uitgedrukt in ruistemper  
waargenomen signaal is  
ongeveer 10K tot 30K.